Fox Island Laboratory
Beach Change Study

ManTech Systems Engineering Corporation

Pacific International Engineering PLLC

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Conversion Factors

Where possible in this report, dimensional quantities are expressed in SI-units with American Customary (non-SI) units following in parentheses. In figures and graphs, dimensions and quantities originally published in non-SI units may have been retained for convenience. Non-SI units can be converted to SI-units using the formulas in the following table.

Conversion of Non-SI to SI-Units of Measurement

Multiply:	By:	To Obtain:
feet	0.3048	meters
miles (U.S. Nautical)	1.852	kilometers
miles (U.S. Statute)	1.609347	kilometers
cubic yards	0.7645549	cubic meters

1. Introduction

1.1 Background

The Fox Island Laboratory (FIL) is a U.S. Navy facility located on the southwestern shore of Fox Island, located west of Tacoma (see Figure 1). A pier constructed in 1969 at the FIL extends across the shoreline into Carr Inlet, and floating craft are moored at the end and alongside the pier. Beach sediments at this shoreline are actively transported by waves generated in Carr Inlet. Since the time the U.S. Navy barges have been moored at the FIL (about 1965), the shoreline has grown seaward at this site, forming a salient. The crest of the salient is now about 30 meters (m) [100 feet (ft)] seaward from the pre-FIL high water line. Shorefront property owners near the FIL perceived that their properties have experienced loss of beach material, damage to bulkheads and seawalls, and even potential structure damage to shorefront homes.

1.2 Objectives

Management Technology International Corporation (ManTech) commissioned Pacific International Engineering (PI Engineering) to conduct a study for FIL to accomplish three main objectives. Those objectives are:

- Determine the factors that have led to the current condition of the shoreline and beaches;
- Estimate the relative contribution of each factor to the overall result; and
- Evaluate alternatives that were presented in the Stabilization of In-Water Floating Facilities Environmental Impact Statement.

1.3 Study Approach

The study approach follows this sequence:

- Specify processes active at the site;
- List relevant factors that could influence the shoreline;
- Develop hypotheses of shoreline responses to the factors;
- Determine data required to quantify those processes;
- Analyze the data and model processes and structural configurations to describe their effects on the shoreline; and

- Conclude the relative effect on the shoreline by the significant structures and factors.

1.4 Study Scope

The scope of the study includes data collection, review and analysis, examination of the shore conditions through geomorphic assessment, and visual assessment of coastal structures. Aerial photographs were also purchased and analyzed for comparison of shore position. Previous topographic and bathymetric survey data and new deep-water bathymetric surveys were acquired to document shore and offshore bottom surfaces. The data were compared to quantify volume change and profile change at and near the salient. Numerical modeling of wave transformation, sediment transport, and shoreline change was accomplished to simulate shore impacts under specified conditions, so that relative impacts from selected factors could be determined.

2. Description of FIL Facilities

A barge associated with the FIL operations is moored at the site and had been for several years before the FIL was built out to its current configuration. A photograph dated 1965 shows a barge moored about 90 m (300 ft) offshore, and the shoreline in the lee of the barge is slightly wider than the adjacent shoreline. The shoreside facilities and the rock revetment protecting the FIL upland were constructed in 1969. A pile-supported pier extends 56.1 m (184 ft) from the high water shoreline into Carr Inlet to serve the barges moored at the pier.

The configuration and size of the barges comprising the in-water facilities have changed over the years. The water depth under the barges varies with the barge draft as well as with tide level, thus varying any potential effect the barges may have locally on coastal processes.

At the time of a site assessment on July 8, 2002, the 10.4-m-wide (34-ft-wide) YFN-912 barge was moored seaward from the end of the pier. Two 9.1-m-wide (30-ft-wide) barges separated the YFN-912 from the 16.8-m-wide (55-ft-wide) M-241 barge. Outboard of the M-241 is the 6.1-m-wide (20-ft-wide) RCB. Therefore, barges of varying lengths occupy about 43 m (140 ft) of distance seaward from the end of the pier. The longest barge, the M-241, is 61 m (200 ft) long. Figures 2 and 3 illustrate the configuration of in-water facilities on July 8, 2002. The RCB was moored on the southeast side of the pier from 1993 to 2001.

Modification of the FIL facility is planned in the form of changing the barges and extending the pier. The analyses presented in Section 5 of this report address the existing conditions and do not apply to any modifications. The analyses presented in Section 6 address three alternative modifications to the facility.

3. Review of Coastal Processes and Geomorphology

3.1 Wind

Figure 4 is a wind rose showing the percent occurrence of winds as a function of direction of origin. The wind rose was developed from hourly wind measurements at the FIL between October 29, 1999 and July 30, 2002. Winds most relevant to the study of coastal processes near the FIL are winds over the wave generating area in Carr Inlet. The majority of waves originate from the south-southeast and from the west-southwest. The longest period of record of wind data in the region is at the SeaTac airport. Data sets are available at other nearby airports, but the FIL data was judged to be most useful to analysis of wave processes because accurate wave direction is of overriding importance. Data collected at locations even as close as Tacoma, Bremerton, or SeaTac are thought to introduce more uncertainty due to direction error than gain of statistical accuracy of projections made with their longer records. A detailed analysis of wind data measured at FIL and at Tacoma Industrial Airport was completed by Miller, *et al*. (2002). Local topographic controls are thought to strongly affect wind direction at the Fox Island shore. Therefore, the basis of calculating waves for sediment transport modeling was the FIL wind data.

3.2 Waves

Waves at the site are mostly wind-generated storm waves and occasionally vessel-generated waves. No wave measurements at the site are known to exist. A video recording of storm waves approaching the FIL from the south and propagating into the lee area of the barges was made available and illustrates wave heights experienced at the site. For the present study, waves were hindcast with the 2.5-year wind record at FIL.

3.3 Tides

The mean higher high water (MHHW) level predicted for Horsehead Bay in Carr Inlet is 4.1 m (13.5 ft) above mean lower low water (MLLW) (Nautical Software 1998). The mean tide level is 2.4 m (7.8 ft) above MLLW. Tides are semi-diurnal, and the mean range is 2.9 m (9.6 ft). Tidal current measurements are not known to exist for this site. Predictions for the west end of Hale Passage list the average maximum ebb current speed at 0.93 meters per second (m/sec) (1.8 knots). Tidal currents are not expected to be a factor in sediment processes at the FIL or adjacent shore.

3.4 Sediments

Beach material in the study area is derived from upland sources. The material is transported alongshore and is sorted and distributed across shore in the process. Episodic failures of bluffs of glacially-derived sands, gravels, and cobbles is inferred to be the main mechanism of generating beach sediments, which Downing (1983) states is the general case for Puget Sound. Stream discharge to this shoreline is minor. The beach material is mixed sand and gravel. Gravel is concentrated in the surface layer of the salient and the adjacent beaches. The gravel layer is generally one or two particle diameters thick where gravel is found on the beach, but is several inches thick on the salient. Below the surface layer, sand and shell hash is found in greater abundance. At some places to the northwest of the FIL, hardpan is exposed at the beach. Locations of predominantly sand were lower on the profile (near mean low water level) on the day of the site assessment. Data from sediment samples and grain size analysis are presented in Appendix B.

Schwartz and Harp (1982) describe segments on the Fox Island shoreline in which sediment sources, transport pathways, and sinks are contained. These segments are termed littoral drift cells. The cell containing the FIL was interpreted from field observations to have a dominant direction of sediment transport to the southeast. The directional pattern of waves in this area, determined from wind data, indicate that although wave direction can be from northwest to southeast here, most of the larger waves traveling past the FIL propagate from southeast to northwest. Schwartz and Wallace (1986) estimated the average net transport rate at the site, based on the growth rate of the salient, to be 634 cubic meters per year (cu m/yr) [829 cubic yards per year (cu yd/yr)]. This estimate assumes that all net sediment transport is captured by FIL facilities. Miller, *et al.* (2002) investigated several methods of computing longshore transport and reported an annual net transport volume of 3,166 cu m (approximately 4,141 cu yd) to the north for 2001, and 1,499 cu m (approximately 1,961 cu yd) to the north for 2000. Estimation of these annual rates might appear to be variable, but environmental forcing is also variable. The main disagreement noted is the direction of transport. Process-based modeling will be the basis of transport volumes and directions reported in the current study.

3.5 Engineered Structures

Bulkheads and riprap have been installed at many locations along the shore to the northwest of the FIL, presumably to protect the upland properties from wave and debris damage (Figure 5). The toe of the structures in most cases is within reach of storm wave runup at high tide. Two damaged bulkheads are visible along the shore a few thousand feet northwest of the FIL. In contrast, few bulkheads and riprap placements exist at the shore to the southeast of the FIL.

The FIL armored the shore fronting its main building at the time of construction, but wave runup cannot now reach the rock revetment. A pile-supported pier, with bents spaced at 6.1 m (20 ft), crosses the shore to reach the barges moored in Carr Inlet. From 1993 to 2001, a 18.3-m-long (60-ft-long) barge (RCB) was moored alongside the pier. At low tide levels, the barge came into contact with the bottom, so the RCB partially had the effect of a groin. In 2001, the RCB was removed from that inshore location and placed outboard of the large barge (M241). Woody debris has been tossed by storm waves on top of the salient, and might have a stabilizing effect on the surface gravel when exposed to high runup. Woody debris is present at the back beach in both directions from the FIL and, under most conditions, functions as shore protection.

4. Methods of Analysis

This section outlines the tools, techniques, and data analysis applied to the evaluation of impacts of the FIL and other identified factors such as bulkheads and riprap revetments that influence shoreline configuration and sediment transport in the study reach.

4.1 Shoreline Change and Geomorphology

Shoreline changes and geomorphological features including the salient, back beach, foreshore, and nearshore slopes were interpreted and analyzed using results of previous studies, ground-level photography, vertical aerial photography, and bathymetric surveys.

Coastal processes including two-dimensional wave transformations, wave-induced nearshore currents and circulation patterns, sediment transport rates, and shoreline evolution patterns have been assessed using numerical simulation tools. The input parameters and boundary conditions for the numerical modeling are derived from the preceding review of coastal processes, and from the analysis of shorelines and geomorphology that follows.

4.1.1 Ground-level Photography

Numerous ground-level photographs were acquired during a site visit on July 8, 2002. The photos were referenced in interpreting shoreline features including the salient, back beach, foreshore, bluff, and various engineered structures in the study reach.

4.1.2 Vertical Aerial Photography

Aerial photographs were acquired for 1942, 1965, 1970, 1978, 1985, 1995, and 2001 (see Appendix C). The photographs were digitized and rectified using the PCI-Geomatica Ortho-Engine software and the available camera calibration information provided with the photographs. A series of ground control points was selected throughout the coverage area using a digital ortho-rectified quadrant (DOQ) photo purchased from the U.S. Geological Survey (USGS) and a Digital Elevation Model also acquired from the USGS. Root-mean square error in horizontal pixel position of the ortho-rectified photos was approximately 2.4 pixels with pixel resolution of 1 m (3.3 ft).

Reference features interpreted from the photographs, including the edge of the shore bluff, seaward edge of vegetation, and the average high water line were digitized manually for a small selection of images (1942, 1965, 1970, 2001) to examine potential changes in horizontal position of these features over time. Typical uncertainties in the identification of these features were determined to be ±5 to 10 pixels, leading to a total uncertainty of ±13 m (±43 ft).

Despite the relatively large total uncertainty in reference feature data, the photographs provided interpretive information of value to the analysis. Such information included the presence and position of engineered structures, including FIL facilities, bulkheads, riprap revetments, salient development and evolution, shoreline plan form in the study reach, bluff edge location, and location of bluff failures.

4.1.3 Bathymetric Surveys

Bathymetric surveys of the project site for 1969 and 2002 were acquired and analyzed as part of the present study. The 1969 bathymetry was acquired in hard copy form. The survey was digitized and adjusted to the MLLW datum. The 1969 survey is centered on the FIL site and extends approximately 100 m (300 ft) alongshore and offshore to a depth of 12 m (38 ft).

The 2002 bathymetry was compiled from three surveys conducted on June 2, 2002, August 21, 2002, and September 10, 2002. The datum for these surveys was referenced to a temporary benchmark on the pier. Leveling from the temporary bench mark to the water surface at the shore at a time of known predicted tide level allowed the conversion of the surveys to approximate MLLW datum. The accuracy of the predicted tide level is thought to be ±0.15 m (±0.5 ft). The June 2, 2002 survey extends approximately 600 m (2,000 ft) along the shore and offshore to a depth of 15 m (50 ft). A contoured surface based on the June 2, 2002 survey is shown in Figure 6 superimposed on the DOQ acquired from the USGS. The additional surveys were requested because the area under the barges at the FIL and the lower part of the bottom slope (deeper than 50 ft) were not surveyed in the June 2, 2002 survey. A composite bathymetry including data from all three 2002 surveys and also showing the alignment of the barges is shown in Figure 7.

Vertical differences were calculated between the overlapping sections of the 1969 and 2002 bathymetry surfaces to derive a net elevation change surface. Net elevation change magnitudes are multiplied by respective surface areas to determine net volume changes for comparison with sediment volume fluxes derived from transport rate analysis described below.

Cross-section profiles of the beach and nearshore topography were extracted from the bathymetry surfaces for analysis of bottom slopes, bottom elevation changes, and profile features. Figure 8 shows the 1969 survey area overlaid on the survey of June 2, 2002, the overlapping portion of the surveys used for difference calculations, and the cross-section profiles.

The MHHW contour relative to a geo-referenced baseline was digitized from the 2002 composite bathymetry for use as a shoreline position in the shoreline change modeling described below. Certain modeling cases simulate the pre-FIL shoreline. In those cases, the pre-FIL shoreline was estimated by adopting the 2002 shoreline and smoothing through the location of the salient, following the pattern observed in pre-1970 aerial photographs. Horizontal and vertical measurement of the shoreline from surveyed elevations is more accurate than can be achieved by using the proxy for the shoreline based on aerial photographs (Ruggiero, *et al.* 2002; Daniels and Huxford 2001). Estimation of the pre-FIL shoreline was deemed appropriate for this application because modeling of absolute, quantitative measures of shoreline position was not the goal. Determination of relative differences caused by structural alterations is the goal.

4.2 Numerical Modeling of Coastal Processes

Numerical models were applied to predict nearshore wave patterns, wave-induced nearshore circulation, and nearshore sediment transport rates in the vicinity of the FIL. The wave refraction, diffraction and reflection model COASTOX, and the wave-induced nearshore circulation model COASTL (MacDonald 1998) were used to simulate waves and longshore current velocities, specifically in the area between FIL barges and the shore. Both models have been verified in a range of different nearshore and coastal environments. Shoreline response and longshore sediment transport rates were predicted using the GENESIS model (Hanson and Kraus 1989).

The COASTOX model is a finite difference, linear wave model for the simulation of wave refraction, diffraction, reflection, and transmission. The model is based on the hyperbolic approximation to the mild slope equation, and can be run efficiently in steady state and in the time domain. The model is appropriate for evaluating the detailed interaction of waves in the vicinity of structures and complex shoreline configurations.

The COASTL model is a finite difference model composed of two independent, but fully dynamically coupled modules; a combined refraction-diffraction wave module and a depth-averaged coastal flow module for the prediction of wave-induced currents. The model is appropriate for application at scales of tens of meters, as in the present study. The flow module computes the steady-state depth-averaged flows resulting from any combination of wave, wind, and tidal forcing.

Boundary conditions for the modeling were based on the composite 2002 bathymetry and detailed information on the dimensions of FIL barges. Grids were also developed including and excluding the FIL barges to represent alternative configurations. Hydrodynamic forcing parameters were developed from wind data and wave data from the Battelle study (Martin *et al.* 2002) and available tidal data.

Two storm waves were modeled:

- *Storm 1*. Waves from the south; wave height (H) of 1.0 m (3.3 ft); wave period (T) of 3 seconds (sec); direction of incident wave approach (DIR) of 170 degrees (deg); and
- *Storm 2*. Waves from the west-southwest; (H) of 1.0 m (3.3 ft); T of 3 sec, and DIR of 250 deg.

Southerly storms are most likely to occur during late fall, winter, and early spring. Northwesterly storms occur mainly in summer and early fall. Tide elevations used for the modeling were low tide (0.0 MLLW) and high tide [2.7 m (9.1 ft) MLLW].

Shoreline change modeling was conducted to develop qualitative estimates of contributions to shore erosion and accretion by FIL facilities and other coastal structures, specifically bulkheads and revetments. A numerical model, GENEralized Model for Simulating Shoreline Change (GENESIS), was applied to a portion of the Fox Island shoreline containing the FIL and extending approximately 670 m (2,200 ft) on either side of the pier. GENESIS was developed to simulate long-term shoreline change on an open coast as produced by spatial and temporal differences in longshore sand transport (Hanson and Kraus 1989). The model was chosen to analyze the Fox Island shoreline because GENESIS has the capability to simulate local modifications to wave height and direction caused by various types of in-water structures, as well as wave-driven longshore sediment transport and the alongshore variation of transport determined according to user-specified boundary conditions. The model calculates longshore sediment transport rates and directions from a time series of wave height, period, and direction. The transport rates are specific to each increment of shore, called a computational cell. Sediment volume continuity is maintained in the model, so the shore position of each cell is computed at each time step based on the net gain or loss of sediment and the position at the previous time step.

The strategy followed in this shoreline change modeling was to perform calibration runs to adjust empirical factors with which the model calculates sediment transport rate from wave power, in order to duplicate the trend of shoreline change observed prior to installation of the FIL. Shoreline change is interpreted to be the movement of the bluff position determined from detailed analysis of aerial photographs. Next, the presence of the barge was introduced to the modeled shoreline and the same waves were input as before, to produce a "barge-only" shore condition. The same procedure was followed in simulating a "bulkhead-only" shore condition, and a "barge-with-bulkhead" condition. Comparison of the individually computed shore positions, cell by cell, provides a means of estimating the relative effect of the barge, the bulkhead, and the combination of barge and bulkhead on producing the current conditions of the shoreline.

Wave information with which GENESIS calculated transport was hindcast from wind speed and direction measured with an anemometer at the barge. The derived two years of wave information was assumed to characterize average conditions of a period long enough to cause observable shoreline change (a few decades). This wave input was repeated to provide the length of record necessary for the duration of the simulations. The initial shoreline position was obtained by digitizing the elevation contour near the MHHW elevation from the 2002 survey with respect to a model baseline. For a preliminary determination of bulkhead effects, the location of bulkheads was estimated from ground and aerial photographs, and by visually estimating an average bulkhead toe elevation relative to the MHHW contour. Knowledge of the beach slope with elevation estimates yielded the setback of the bulkhead from the model shore. GENESIS calculations generally represented the growth of the salient in the lee of the barge from 1970 to 2000.

5. Evaluation of Factors Influencing Shoreline Configuration

This section of the report documents the evaluation of factors that influence the condition of the shorelines and beaches in the vicinity of the FIL facility. The evaluation involves:

- Testing the prevailing hypothesis regarding FIL facilities modifying physical processes that result in shore erosion.
- Developing and testing new hypotheses (if required) regarding FIL facilities' influence on physical processes that are responsible for shore erosion.

The prevailing hypothesis concerning the impact of FIL facilities on shore erosion may be described in simple terms as follows:

"Material that is trapped in the salient does not move to adjacent beaches. The development of the salient may therefore exacerbate downdrift erosion by retaining sand and gravel that would otherwise have been transported to the adjacent beaches."

The hypothesis is tested by reviewing previous study findings, analyzing shoreline change and geomorphology in the vicinity of the FIL, and with numerical modeling.

5.1 Impact of FIL on Shoreline Configuration and Sediment Transport

5.1.1 Findings of Previous Studies

It is generally agreed that waves move sediment in both directions along the beach at the FIL. A study by Schwartz and Wallace (1986) determined a net shore drift to the southeast based on accumulations of sediment and debris on bulkhead offsets and ramps. Results from the Coastal Zone Atlas (WDOE 1979) indicate a seasonal variation with southbound transport in spring-summer and northbound transport in winter. Miller, *et al*. (2002) conclude that the predominant wave direction moves more sediment toward the north than toward the south based on a wind-wave hindcast analysis using winds measured at the Tacoma Industrial Airport and at the FIL. Their study also concluded that sediment trapped in the sheltered zone behind the barges does not move to adjacent beaches, but that sediment may not be trapped with 100 percent efficiency; some sediment transported into the sheltered area may be bypassed to adjacent beaches.

The analysis that follows will seek to resolve the discrepancy in previous studies by examining the sediment transport rates and directions, and relative trapping and bypassing efficiency of the salient.

The FIL facility acts similar to a detached breakwater in that the reduction in wave energy in the lee of the obstruction reduces the rate of littoral drift there and produces sediment deposition, resulting in a shoreline bulge or salient in the sheltered area. Some transport may continue to bypass the salient.

Photographic evidence (e.g., Corsi 2001) indicates a distinctive and pronounced asymmetry in the salient with a more concave seaward shoreline to the south of the FIL and a more convex shoreline to the north of the FIL. Figure 9 is an aerial photograph of the FIL salient acquired in 2001, illustrating the asymmetry. The asymmetry might lead to an interpretation of updrift accretion (north side) and downdrift erosion (south side) due to sediment being trapped by the FIL, an idea that is consistent with a north to south net transport direction as suggested by Schwartz (1991).

However, a reasonable hypothesis is that the behavior and development of the salient and its asymmetry are controlled by alongshore gradients in wave direction and wave height, which in turn control sediment transport gradients alongshore.

Analysis of wind measurements at the FIL indicates wind direction has a bi-modal distribution. Wave and sediment transport direction is both northwest and southeast at the FIL. The predominant direction for wind is from the south-southeast (170 deg). Less frequently, winds blow from the west-southwest (250 deg), and with less intensity.

Waves arriving from the south-southeast approach at a highly oblique angle to the local shore, thus producing relatively strong transport to the north. At the FIL, the oblique angle means that a wave energy shadow develops north from the FIL barges. The shadow reduces the transport to the north of the FIL, promoting sediment deposition and salient growth. The pattern of wave approach to the salient shoreline reduces the northward transport locally. However, nowhere on the shoreline is there a point of zero net transport to the north because the shoreline is never perpendicular to the wave approach. Therefore, transport may continue around the salient and allow bypass of sediment to the north side.

Waves from the west-southwest are typically smaller and arrive at an angle that is much smaller relative to shore-normal at the north side of the salient than waves from the south-southeast. The waves of lower height and smaller angle produce a southbound transport rate on the north side of the salient that is less than the northbound rate when comparable waves arrive from the south-southeast. No net transport occurs and no bypassing is possible if the wave angle is perpendicular to the shoreline. The wave shadow for waves arriving from west-southwest is also likely to be much narrower (because of the difference in projected width of the group of barges) than that of waves from the south-southeast. The pattern of unequal transport in the two directions would lead to erosion on the south side of the FIL salient. These concepts are illustrated in Figures 9 and 10.

This conceptual model explains the observed shoreline development in terms of unequal rates of alongshore transport. This hypothesis will be tested through the application of numerical models for waves, currents and sediment transport.

5.1.2 Shoreline Configuration and Geomorphology

Vertical differences were calculated between overlapping sections of the 1969 and 2002 bathymetric surfaces (Figure 11). The difference map shows that net accretion occurred along the FIL shore with a maximum thickness in the middle of the salient and diminishing to the north and south. The volume of accumulated sediment within the area covered by the surveys extending to a depth of approximately 6 m (20 ft) is estimated to be 5,000 cu m (6,500 cu yd).

If the salient grew steadily between 1969 and 2002, the average annual volume of sediment captured from the littoral drift would be 145 cu m (190 cu yd). The accuracy of the 5,000 cu m (6,500 cu yd) estimate may be questioned due to the limited area of survey coverage. Some sediment might have accumulated outside the surveyed area of 1969, which extended only to an 8.5-m (28-ft) depth.

The thickness of accumulation diminishes seaward from the toe if the beach is sloped, and at the depth of approximately 6.1 m (20 ft), the accumulation is negligible. It is suggested that the accuracy of the estimated volume would not be affected by sediment if it were accumulating at the bottom up to the depth of 8.5 m (28 ft).

Bottom elevation differences were also analyzed along three cross-sections oriented perpendicular to the regional shore trend (see Figure 8). The three transects represent the north, center, and south portions of the salient. Figure 12 shows the bottom elevations in 1969 and 2002 along the three transects. Accumulation is evident in each cross-section, mainly in the portion of the beach profile above MLLW. The largest accumulation occurs at section one, approximately at the centerline of the salient. Thickness of the accumulated layer decreases seaward along all sections, and at depths greater than 1.5 m (5 ft) to 3 m (10 ft) no significant profile change is evident.

The trend of bottom changes in Figure 11 shows that the accretion reduces in thickness towards the boundaries of the survey. Based on this observation, it seems likely that most of the volume of sediment in the salient is accounted for in the upper beach. It is assumed that no more than 10 percent of the total volume of sediment is unaccounted for.

A special deepwater survey was requested to investigate loss of sediment from the upper slope to the deep part of the slope. Sediment accumulation at the lower slope and at the toe of the slope would be indicated by sediment loss from the upper part of the slope.

The results of the deepwater survey are presented in Figure 7 and a close-up is shown in Figure 14. Figure 13 also shows a three-dimensional interpretation of the 2002 composite survey. There is no evidence in the survey results that suggests significant filling in deep water.

The slope configuration at the toe of the lower slope offshore from the FIL does not suggest any significant accumulation of sediment. Based on this observation, it is suggested that the amount of sediment lost to deep water at FIL is approximately equivalent to the amount of sediment deposited along the remainder of the shore. Incorporating the above assumptions, the volume of deposition over 33 years is re-estimated at 5,500 cu m (7,200 cu yd), which yields approximately 168 cu m/yr (220 cu yd/yr) of trapped sediment at the salient. Comparison of this amount with the estimated volume of net sediment transport 1,200 – 2,700 cu m/yr (1,600 – 3,500 cu yd/yr) (Miller, *et al*. 2002) shows that FIL facilities may capture approximately 7 percent to 15 percent of the net sediment transport. Considering that the variability of the rate of sediment transport from year to year is approximately 100 percent to 200 percent, it is suggested that the annual rate of sediment capture by FIL facilities on the upper beach is insignificant relative to the net transport.

5.1.3 Two Dimensional Wave Modeling (COASTOX) Results

The results of COASTOX model simulations are presented in Figures 15 through 18. Figures 15 and 16 show the spatial distribution of wave height for Storm 1, and waves arriving from the south-southeast (170 deg), at low and high tide, respectively. Figures 17 and 18 show the spatial distribution of wave heights for Storm 2, and waves from the west-southwest (250 degrees), at low and high tide, respectively. As hypothesized above, Storm 1 creates a shadow zone for waves along the FIL shore to the north of the facilities. It is likely that during this period the northward sediment transport is significantly reduced along the beach to the north of the FIL. At high tide, the position of the barges relative to the shore allows waves to propagate between the barges and shore and a wave shadow occurs north of the

FIL barges. This result suggests that sediment bypasses the FIL and salient mostly at high tide with waves from the south.

Waves from the west-southwest (250 deg) cause a significant but relatively narrow shadow zone behind the FIL barge at both low tide and high tide.

To evaluate the effect of the barges on the wave pattern, the same waves were simulated for the hypothetical situation in which no barges are present, but the shore and bottom bathymetry are the same. The results of the simulations are presented in Figures 19 through 22, and the spatial distributions of wave height differences (with-barges minus without-barges) are shown in Figures 23 through 26. The results indicate significant reduction of wave heights at the shore during low tide and basically no change in wave conditions along FIL shore at high tides during occurrences of waves from the south.

5.1.4 Wave-induced Currents (COASTL)

The results of applying the COASTL model with the existing barge configuration are presented in Figures 27 through 30. The figures show current directions and speeds (vectors) over the modeling domain. The currents simulated by the CoastL model are the time-averaged wave-generated current, not the instantaneous orbital velocities. The color shading on Figures 27 through 30 indicates the depth of water. To show current directions and velocities in more detail in the vicinity of the FIL barges, a close-up view of each figure is also shown. At low tide during waves from west-southwest (250 deg), a significant weakening of current occurs in the wave shadow zone immediately behind the barge, but current resumes at full strength within 50 m (150 ft) of the apex of the salient (Figure 27). Figure 30 shows that during southerly storms at high tide, the longshore current velocities are not interrupted by the presence of the barges and salient. The wave-induced current bypasses the FIL shoreline with potential to move sediment to the north.

At low tide during waves from the south, there is a weakening of the current speed away from the shore at the apex of the salient and for approximately 100 m (330 ft) to the north of the salient (Figure 29). In contrast, at high tide the current is stronger near the shore at all positions north and south of the salient (Figure 30).

A similar procedure for comparing with- and without-FIL cases as described above for the wave height analysis was implemented to evaluate the impact of the barges on wave-generated currents. CoastL modeling was conducted for the hypothetical condition of no-barges at the FIL shoreline. The difference in currents between barges and no-barges for southerly storms is shown in Figures 31 and 32 for low and high tides, respectively. The figures show that significant differences in current velocities occur at low tide and only very small differences occur at high tide along the FIL shoreline. Figure 31 also shows that the northward velocities increase in the vicinity of the barge at low tide, which may enable sediment to bypass the salient during these conditions. Physically, the result makes sense. However, if conclusions were to be based on this result alone, finer scale modeling would be needed to assure that significant bias is not introduced through the course grid resolution.

5.1.5 Shoreline Modeling

The shoreline change model GENESIS was applied to 1,470 m (4,822 ft) of shoreline including the location of the FIL for the purpose of qualitatively determining the effects of the presence of the barges and pier on the shoreline relative to the natural processes without the FIL facility. A simulation period of 30 years was chosen because photographs of the shore are available from the time the facility was constructed and span 30 years. The shoreline without the salient was input to the model and run with 30 years of hourly wave data and with the barges simulated as an offshore structure that is slightly permeable to waves. The model was calibrated by adjusting the user-specified calibration coefficients so that the calculated shoreline shape at the end of 30 years produced a salient of approximately the same location and distance from the original shoreline as the actual salient (measured from the 2002 topographic survey). The model was then applied with the initial shore (no salient) and no barges, to simulate the shoreline evolution under the same environmental forcing, but without the influence of the FIL. The difference between the shorelines at the end of the period for the with-FIL and without-FIL structures is plotted in Figure 33. The figure illustrates qualitatively that the impacts of the FIL on the shoreline are limited to a distance of about 350 m (1,150 ft) northwest, and about 330 m (1,080 ft) southeast from the FIL. Shoreline advance occurs over a shore length of about 150 m (500 ft), and shoreline retreat occurs over a distance of about 530 m (1,740 ft).

5.2 Impacts of Other Factors

The above analysis provides an explanation for the asymmetry in the salient and, furthermore, indicates that the potential for sediment bypassing at the FIL shore segment from south to north during southern storms is higher than the potential for sediment bypassing from north to south during northwesterly storms. Therefore, accumulation of sediment to the north of the shoreline salient is more likely than to the south.

Normally the shore north of the salient would have accumulated a greater percentage of sand-sized sediments and slightly greater sediment thickness compared to the present condition. However, the development of bulkheads to the north of the salient has interfered with this process (Figure 34). Bulkheads and revetments occupy a significant length of the shore north of the salient and have limited development of the upper beach in that area. Sediment on the north side is confined to a smaller sub-areal beach width by the presence of bulkheads. The increased level of sediment dynamics there may result in offshore migration of sediment and losses to deep water outside of the depth of closure.

5.2.1 Shoreline Change and Geomorphology

Upland formations along the shore range from bluffs and steep slopes to low uplands slightly above beach level. Aerial photographs and topographic and bathymetric data reveal the following:

Cross-sectional configuration. The steepness of the overall profile leads to more energetic coastal processes active at the bluff toe than would be the case for a flat, dissipative beach.

Plan view configuration. The shoreline has a rhythmic form with a characteristic amplitude.

Height and steepness of the upland slopes confining the shoreline. Some areas of the upland backing the beach are stable, while other areas show loss of trees and evidence of intermittent slides.

5.2.1.1 Cross-sectional Configuration

A typical cross-section of the Fox Island shoreline is shown in Figure 35. This section is taken to the north of FIL and coincides with Section 2 (see Figure 8). The cross-section consists of a relatively flat upper part and steep lower part of the bottom slope. The upper part of the beach (referenced herein as foreshore) is a relatively narrow shelf that slopes at approximately 15 horizontal to 1 vertical from the bulkhead, or in the case where no bulkhead is present, from the ordinary high water mark to a depth of about 1.5 to 2.5 m (5 to 8 ft) below MLLW. The lower segment of the slope is steep; approximately 3.5 horizontal to 1 vertical extending from a depth of 1.5 to 2.5 m (5 to 8 ft) below MLLW to a depth of at least 90 m (300 ft).

The sediment on the foreshore slope consists of a gravel layer (thickness from a few particle diameters to several inches) overlying gravelly sand that sometimes is underlain with hard pan. Figures 36 and 37 illustrate the type of surface sediment and material composition on the upper foreshore of the project area. Sediments analyzed in a previous study were shown to generally have a slightly higher percentage of sand in the samples collected south of FIL compared to those collected north of FIL, particularly at the higher elevations of the beach. No signs of any significant differentiation are identified based on the sediment grain size analysis. Non-uniformity of the sediment size on the beach to the north and to the south from FIL could be an indication that the FIL and salient present a minor obstruction to the sediment transport from the south to the north, considering that the predominant longshore drift is to the north, or that the greater percent of bulkheaded shoreline to the north influences the sediment composition of the fronting beach.

There are at least two physical processes important to the shoreline stability that relate to the cross-section slope. One is the pattern of wave energy dissipation across the bottom slope and amount of energy delivered to the toe of the bluff or bulkhead. On a typical Fox Island cross-section, most wave dissipation occurs on the upper foreshore where depth of water limits the breaking wave height. The width and corresponding slope of the foreshore are critical for wave energy dissipation and the amount of residual energy delivered to the bluff and bulkheads. On a wider and flatter foreshore part, less energy is delivered to the bluff and bulkheads, therefore less damage should be expected to the bluff, shore structure, and shoreline.

The Fox Island shoreline tends toward a natural equilibrium with the prevailing wave climate by adjusting foreshore width and slope to achieve the required rate of wave energy dissipation. The natural process of widening and flattening of the foreshore slope is accomplished through shore recession. This process continues until dynamic equilibrium between the foreshore width and wave energy dissipation is reached. At this point the shore is stable (in the engineering time scale) and sand and gravel accumulate at the toe of the bluff (e.g., Figure 36).

The second important consequence of cross-sectional profile shape is the stability of the sediment on the upper slope and potential for loss of sediment to deep water due to down slope movement. A narrow upper beach and steep slope promote the permanent loss of material offshore during those conditions in which sediments are in motion. The likelihood that beach sediment will remain in the upper profile is greater for a wide beach than for a narrow and steep beach. Therefore, the process of widening the upper slope as part of the bluff recession discussed above in the context of wave energy dissipation tends to conserve sediment in the littoral system and eventually develop a more stable shore. Interfering with this process by construction of bulkheads (by fixing the bluff toe position) or other coastal structures results in a narrowing and steepening of the foreshore and consequential increased loss of sediment to deep water.

The analysis described above suggests that the natural development of the Fox Island beach profile has not been significantly impacted by FIL facilities. In the vicinity of FIL facilities, there has been a reduction of wave energy by the presence of the barges and a widening and flattening of the foreshore due to the formation of a salient. In general, these features have adjusted to the local wave climate and achieved a natural dynamic equilibrium.

On the other hand, the bulkheads and revetments constructed along a significant part of the shore to the north of the FIL facilities have impacted the formation of an equilibrium cross-section. The bulkhead structures have limited widening of the foreshore and the formation of an equilibrium slope. This has led to narrowing of the foreshore slope and increased the loss of beach sediment to deep water.

In summary, the FIL facilities have not altered the natural tendency for a stable cross-section configuration of the Fox Island shoreline to develop. However, the system of bulkheads constructed predominantly after FIL facilities may contribute significantly to profile instability and exacerbate shore erosion. This hypothesis will be further tested through application of the GENESIS model in Section 5.2.2.

5.2.1.2 Shoreline Rhythmicity

The Fox Island shoreline displays a rhythmic form, having a length and amplitude that is approximately repeated (Figure 38). The amplitude and length of rhythmic plan form shape depends on numerous factors including geology of the coastline, waves and currents, type and availability of sediment, and shore and offshore structures. In the case of Fox Island's shoreline, these offshore structures are barges. The concave form can develop where shore material is more easily eroded or the supply rate of upland sediments is diminished. Convex forms can develop where hard points are exposed or constructed or offshore structures shelter the shore from wave energy. The overall pattern at the Fox Island shore is imposed mainly by the geological history. The effect is to influence the patterns and rates of net transport in the longshore direction. Evidence of that is seen in areas of healthier beaches alternating with areas of narrower, sediment-starved beaches visible in the aerial photographs. By examining the FIL and shore protection structures in this context, it is evident that the area north of FIL has less natural accumulation of sediment than the area south of FIL.

5.2.1.3 High Upland with Steep Slopes

Most of the Fox Island shore is backed with a bluff or steeply sloping upland. The elevation at some locations reaches 60 m (200 ft) above the beach level. Figure 39 is an example of the upland slope that is undergoing failure. The upland is composed of glacial till (sediments consisting of clay and silt through sizes up to cobbles). Hard clay, interpreted to have deposited in a glacial lake and to have consolidated, crops out at the beach level.

The upland slope has been failing at identifiable locations for a long time. Several mechanisms have been contributing to the process. A main cause is undermining of the toe of the slope by wave forces. The presence of clay in the slope material is also a factor contributing to slope failure because of saturation of the overlying sediments during the rainy season. The sediment generated by bluff failure is transported by waves and currents and supplies the littoral system. Bluff material is the major source of sediment supplied to the beach of the study area. Maintenance of a stable beach in a given wave climate requires a certain volume of material to feed to the littoral system. Bluff material that feeds the system in turn is a product of slope failure and shore retreat. A quasi-steady rate of retreat of the slope toe can be expected when littoral processes remove the sediment contributed to the beach by slope failure. Restricting retreat of the bluff toe and slope failure, therefore, lead to a deficit of sediment in the littoral system and acceleration of loss of beach sediment.

Geomorphic indicators imply that bulkheads exacerbate impact from FIL and extend it to the area outside the FIL shoreline. This effect was tested with numerical modeling and is reported in the following section.

5.2.2 Shoreline Modeling

The presence of bulkheads at the backbeach was modeled with GENESIS to illustrate the possible effect in the alongshore direction of a bulkhead if the shore retreats to the bulkhead. In the case modeled here, exact location of all bulkheads is not known. Precise modeling of the scour process at the bulkhead toe, accounting for the toe elevation and mobility of material at the toe of the structure, would require more precise input data and could be modeled only with a more advanced model than GENESIS. Bulkhead positions were estimated from observations made in the site assessment and were coded into GENESIS, as was the existing shoreline. A 30-year simulation was made with barges of the FIL in place, with and without the bulkhead. The difference in computed shoreline position at the end of the two simulations is shown in Figure 40. Where the plot of the difference is above the zero line, the shore retreated more with the bulkhead, relative to retreat without the bulkhead. The figure shows that at locations where the shore retreats to the bulkhead, the erosion progresses alongshore, affecting a greater length of shore than if the bulkhead had not been in reach of the erosion process. This difference shows the separate effect of the bulkhead, but within the context of the FIL existing at the site. Comparison of Figure 40 with Figure 34 illustrates qualitatively the difference between the effects of the FIL only and the bulkhead only, although the simulations started in the first comparison with a pre-FIL shoreline, and in the second case with the salient and the FIL.

6. Evaluate Alternatives in EIS

6.1 Description of Alternatives

An Environmental Impact Statement (EIS) for the Stabilization of In-Water Facilities at the FIL is being prepared by Adolfson Associates under contract to Engineering Field Activity, Northwest, Naval Facilities Engineering Command. Alternatives developed in the EIS consisted of various configurations of the pier and barges, with various barge dimensions. The alternatives were analyzed from the standpoint of impacts to sediment transport in the manner described in the preceding report sections. Results of that alternatives analysis comprise this section.

Action alternatives considered in the EIS involve two components: replacing the existing configuration of pier and barges with a more stable platform, and replacing existing mooring components. The No Action Alternative and the Replace Moorings Alternative have the same barge dimensions configuration as the existing condition, which was analyzed in the previous sections. Results are reported here as Alternative 1. Alternative 2 is the addition of a 73 m-long (240-ft-long) pontoon 18.3 m (60 ft) wide at the end of an extended access pier. Alternative 3 is the replacement of the pontoon of Alternative 2 with a 110 m-long (360-ft-long) pontoon 183 m (60 ft) wide. The arrangement of the barges in each alternative is illustrated in Figure 41.

6.2 Evaluation of Criteria

Alternative barge configurations were analyzed for their impact, relative to the existing condition, on longshore transport and shoreline position. The alternative configurations of the FIL barges would create different rates of sediment transport in their lee, and different impacts on the dimensions of the existing salient. The potential transport rates at areas of interest in the model grid can be calculated with output from some wave propagation models, and beach changes can be inferred from the calculation results. Potential sediment transport rate is the rate that could be attained under the given wave forcing if there were no limitations on the availability of sediment to be transported. In most circumstances the actual rate is less than the potential rate. Potential rate is used in this analysis because it is a quantity determined consistently from one simulation to another and is more simple to obtain than is actual transport over short intervals.

The alternatives are assessed to compare their effects on wave propagation and sediment transport rates relative to the existing condition. The numerical models provide quantitative output, but output values of wave height and transport rate simulate only a few selected conditions. The simulations were selected to represent significant transport events over the long-term. The model does provide a consistent means of comparing effects of one structural alternative with another when input waves are identical for the alternatives. With judicious selection of the input conditions, although limited in number, analysis of output can provide a means of evaluating the relative effect of the alternatives on sediment transport, availability of material to the beach, and salient volume.

6.3 Methods of Analysis

Tools for comparing the shoreline effects of the alternatives are the numerical models COASTOX and CoastL. The COASTOX model is a finite-difference, linear, monochromatic wave transformation model which is based on the wave ray approach for step-wise calculation of wave number. The governing equations include the effects of diffraction, refraction, reflection, and energy losses due to bottom friction and wave breaking. The modeled area is represented by many computational nodes at which the wave elliptic equation is solved over a series of time steps. The model is based on the hyperbolic approximation to the mild slope equation, and can be run in steady-state and in the time domain. The resulting calculated wave heights are averaged at each node and listed as output. Visualization of the output is accomplished by importing the wave height results to commercially available plotting software to produce color-coded spatial distributions of wave height.

The model CoastL simulates wave-induced nearshore circulation. The model is composed of two independent, but fully dynamically coupled modules: a combined refraction-diffraction wave module and a depth-averaged coastal flow module.

The wave module uses a wave-period averaged technique and can, therefore, be used over areas ranging from tens of meters to tens of kilometers. Approximate non-linear effects are included in random waves in the surf zone. Full wave-current interaction between internally generated or externally imposed flow fields is also included.

The flow module computes the depth-averaged flows resulting from any combination of wave, wind, and tidal forcing. The CoastL model can be run in wave-only, current-only, or wave-current modes. Output wave-generated current speeds at node points are represented as vectors. Computed variables are combined as terms in sediment transport formulas, and potential transport at model nodes is produced as a separate file, for input to visualization software.

Wind direction controls the direction from which waves approach the Fox Island shore, and is constrained by regional and local topography and weather patterns. Wave directions selected for analyzing impacts of FIL alternative configurations were based on local observations that larger waves arrive from predominantly two directions, south-southeast and west-southwest. Because modeling waves and resulting sediment transport caused by every combination of wave height, period, direction, and tide level is impractical, a procedure was followed to select a limited number of combinations that are meaningful to the shore processes at the FIL. Tide level and wave height (and associated period) for model input were selected by analyzing the joint occurrences of tide level and wave height at this location. The focus of the analysis was to identify those wave characteristics having magnitudes and frequency of occurrence that are significant to sediment transport and shoreline change. Those waves were selected by identifying occasions when wind speed was greater than 9 m/sec [20 miles per hour (mi/hr)]. Waves were hindcast with a range of wind speeds from both the south-southeast and the west-southwest. The hindcasts showed that wind speed from either of those directions that was less than 9 m/sec (20 mi/hr) did not produce a wave height that was significant to sediment transport. The threshold wave height was selected to be 0.15 m (0.5 ft).

The hourly wind speed and direction data recorded at the FIL from October 1999 to July 2002 were sorted with the associated date and time to select only those events greater than 9 m/sec (20 mi/hr). Date, time, and wind speed and direction of those events were input to a wave hindcast procedure. Waves of the height that are significant for sediment transport were not predicted for all these selected wind data due to some winds blowing from a direction having a short fetch. The resulting waves of significance were thereby associated with a date and time. Tide prediction software was employed to tabulate tide levels near the FIL corresponding to the significant wave events. A calculation routine was written to organize the wave height and tide elevation data into a table listing the frequency of occurrence (as a fraction of the total wind records) for each combination of wave height and tide elevation. Wind recordings were missing for 16 percent of the total time between start and end of the data record. The missing records appeared to be distributed randomly through time, so the frequencies of occurrence statistics were assumed to adequately represent the time period. Under that assumption, the occurrence statistics expressed as a percent would not be significantly different if the wind record had been 100 percent complete. The resulting distribution showed maximum joint wave height-tide elevation occurrences at tidal elevations of 2.6 m (8.5 ft) and 3.8 m (12.5 ft). Wave heights selected for analysis with these tidal elevations are 0.4 m

(1.4 ft) and 0.8 m (2.6 ft), with periods of 2.5 sec and 3.2 sec, respectively.

Two combinations of tidal elevations and wave heights with associated periods, each with wave directions from 170 and 250 deg, were input to wave propagation models in which the four alternative FIL configurations were represented, resulting in 16 simulations. The four configurations are described in Figure 41. Their geometry and location were coded into the model grids for simulating wave propagation. COASTOX simulation results provided wave heights in the vicinity of the FIL and along the shore zone for a distance of 400 m (1,300 ft) from southeast to northwest of the FIL. CoastL model output provided longshore current velocity and terms for calculating longshore sediment transport potential at each computational node in the same area. Comparing results from simulations in which only the barge configurations differ shows effects of the alternatives relative to one another on waves, wave-generated currents, and longshore sediment transport potential at selected points in the model grid.

6.4 Results

Waves. Results of COASTOX modeling of wave interaction with the FIL alternatives are displayed graphically in Figures 42 through 45. The figures represent average wave height and indicate zones where waves are blocked by the barges, wave height is increased and decreased through wave reflection and diffraction, and the pattern of energy is spread through shoaling, refraction, and lateral propagation into areas of lower energy. Close examination of the figures reveals differences in the patterns of wave height in the lee of the barges and along the shore. The barges in all alternatives, when subjected to waves from the south, project a wave energy shadow at the shoreline of the salient north of the pier (at the cusp of the salient). Alternatives 1 and 4, however, produce the shadows of the smallest sizes in Figures 42 and 43. Wave energy from the west is reflected and blocked by the barges to produce a shadow zone at the salient shoreline southeast of the pier and, as with waves from the south, Alternatives 1 and 4 cast the smallest shadows.

Longshore Transport. Qualitative comparisons of wave energy distribution along the shore can be drawn from the COASTOX output, but computational capabilities of CoastL provide insight into effects on processes more directly associated with sediment transport and shoreline change. CoastL output of Alternative 1 for example is shown graphically in vector plots in Figures 46 and 47 to represent the effects on longshore transport when waves approach from the south and west, respectively. For the same incident wave height and period, waves from the south generate faster current speeds at the shore than do waves from the west, which carry sediment that has been mobilized by breaking waves. That is a logical result when considering the longshore component of the angle of wave approach to the shore segments. Similar differences are shown in output of Alternatives 2, 3, and 4, although the individual plots are not shown here.

Wave-generated current information and sediment sizes were combined with other parameters derived in the modeling to yield potential transport, a more useful quantity for projecting shoreline change. Coarse gravel is present in the mixture of beach sediments, but the sediment size input to the calculation procedure was coarse sand and fine gravel because that is the range in which the empirical transport formulas are valid. Differences in transport vector patterns between Alternative 1, as the basis of comparison, and Alternatives 2, 3, and 4 are of greater interest because with that information, inferences can be made regarding the relative change in nearshore sediment transport patterns and intensities. The current barge configuration is Alternative 1, so changes from existing conditions can be estimated by comparing effects of Alternative 1 with those of the other alternatives.

Patterns of computed transport potential for Alternative 1, for example, are shown in Figures 48 and 49 for the higher wave heights with waves from the south and from the west, respectively. The figures show that waves from the south drive transport along the shore from southeast to northwest with fairly uniform intensity until a point is reached northwest of the cusp of the salient. With Alternative 1, beach material is driven around to the northwestern portion of the salient by waves from the south, where transport decreases. Waves from the west, however, interact with the Alternative 1 barge configuration to produce moderate transport intensity on the northwest shore, the most intense transport over the cusp of the salient, and very low transport rates on the southeast side of the salient. A small zone of transport reversal was noted just northwest of the salient. A transport nodal point, where divergence of transport would tend to cause net removal of sediment under attack by waves from 250 deg, is located about 20 m (70 ft) northwest of the FIL pier. A convergence zone, where sediment would tend to accumulate, is indicated at a location 70 m (200 ft) northwest of the pier. Obviously, the location of the node and convergence zone would vary greatly with the angle of wave approach. These interpretations of model results relate to specific conditions, and although selected to represent more general behavior when significant transport occurs, quantitative predictions of future behavior in the natural environment cannot be made without a large data collection and model calibration effort, which is beyond the scope of this analysis.

Differences in transport potential of Alternatives 2, 3, and 4 compared with the existing condition (Alternative 1), are plotted to emphasize transport magnitudes in Figures 50 through 55. The color patterns indicate intensity of transport differences and illustrate where changes in shoreline position could result from the changed transport. The amount of change in shoreline position or alignment depends on the amount of change in transport caused by implementing an alternative different from the current configuration. Figures 50 and 51 show that with waves from the south, Alternatives 2 and 3 decrease transport from current conditions at the cusp of the salient. Alternative 4 (Figure 52) is shown to decrease sediment transport at the cusp to a lesser amount, but increase transport on the northwestern portion of the salient. With waves from the west, Alternatives 2 and 4 (Figures 53 and 59) are shown to decrease transport southeastward from the FIL pier for a distance of about 15 m (50 ft). Alternative 3 (Figure 54) shows a similar pattern of transport decrease compared to existing condition, but the longshore extent of decreased transport rate is about 50 percent greater than those of Alternatives 2 and 4. Also with waves from the west, Alternative 3 produces decreased transport at the southeastern most portion of the modeled shoreline, indicating an increased shadow zone relative to the other alternatives. The magnitudes of the differences shown on the figures apply to the area represented by a grid node, almost 2.3 square meters (sq m) [25 square feet (sq ft)], for the identified wave condition.

As a means of numerically comparing the effects of the alternatives with existing conditions, the model grid was divided into five longshore regions southeast of the cusp of the salient, and five northwest of the cusp, all of equal length as shown in Figure 56. Longshore transport rates calculated at each node were averaged within the regions, and the averages for each region for each simulation are listed in Table 6-1. The differences in averages tabulated for the alternatives indicate the differences among the alternatives for the specific waves and water levels. In all cases the differences are quite small, which indicates that the effect of implementing an alternative different from the current configuration would have only a small change in transport and, therefore, shoreline alignment.

Table 6-1. Longshore Transport Rates Calculated for Alternatives

	Alternative				Difference		
	1	2	3	4	2 - 1	3 - 1	4 - 1
3.8-m (12.5-ft) Tide and Waves from the South							
1	0.20	0.05	0.10	0.06	-0.15	-0.10	-0.14
2	0.18	0.03	0.03	0.04	-0.15	-0.15	-0.14
3	0.06	0.01	0.01	0.00	-0.06	-0.05	-0.06
4	0.03	0.01	0.00	0.03	-0.02	-0.03	0.00
5	1.38	1.47	0.64	2.26	0.09	-0.74	0.88
6	1.07	0.94	1.14	1.13	-0.13	0.07	0.07
7	1.33	1.18	1.27	1.30	-0.15	-0.06	-0.04
8	2.89	2.73	2.56	2.90	-0.16	-0.33	0.01
9	1.94	1.88	1.95	2.00	-0.06	0.01	0.06
10	0.88	0.86	1.04	0.98	-0.02	0.15	0.10
2.6-m (8.5-ft) Tide and Waves from the South							
1	0.08	0.01	0.02	0.02	-0.07	-0.05	-0.05
2	0.04	0.00	0.01	0.00	-0.03	-0.03	-0.03
3	0.01	0.00	0.00	0.00	-0.01	-0.01	-0.01
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.05	0.13	0.02	0.22	0.08	-0.03	0.17
6	0.12	0.11	0.11	0.16	-0.01	-0.02	0.03
7	0.26	0.23	0.25	0.27	-0.03	-0.01	0.00
8	0.20	0.19	0.20	0.20	0.00	0.00	0.00
9	0.19	0.16	0.18	0.18	-0.02	-0.01	-0.01
10	0.14	0.13	0.14	0.14	-0.01	0.00	0.00
3.8-m (12.5-ft) Tide and Waves from the West							
1	0.20	0.18	0.19	0.18	-0.02	-0.01	-0.02
2	0.58	0.60	0.65	0.69	0.02	0.07	0.11
3	0.76	0.86	0.95	0.95	0.10	0.19	0.19
4	0.56	0.74	0.61	0.78	0.18	0.05	0.22
5	0.79	0.51	0.16	0.45	-0.27	-0.62	-0.34
6	0.13	0.03	0.00	0.04	-0.11	-0.13	-0.09
7	0.13	0.07	0.02	0.06	-0.07	-0.12	-0.07
8	0.72	0.55	0.21	0.52	-0.17	-0.51	-0.19
9	1.61	1.21	0.81	1.42	-0.40	-0.80	-0.19
10	2.27	2.56	2.22	2.04	0.29	-0.05	-0.23

	Alternative				Difference		
	1	2	3	4	2 - 1	3 - 1	4 - 1
2.6-m (8.5-ft) Tide and Waves from the West							
1	0.20	0.19	0.22	0.20	-0.01	0.02	0.00
2	0.26	0.24	0.27	0.25	-0.02	0.01	-0.01
3	0.19	0.17	0.19	0.19	-0.02	0.00	0.00
4	0.18	0.15	0.17	0.17	-0.03	-0.01	-0.01
5	0.11	0.06	0.02	0.06	-0.06	-0.09	-0.05
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.04	0.02	0.00	0.02	-0.01	-0.03	-0.01
8	0.15	0.09	0.06	0.11	-0.06	-0.09	-0.04
9	0.26	0.22	0.22	0.24	-0.04	-0.03	-0.01
10	0.35	0.29	0.35	0.34	-0.06	0.00	-0.01

7. Conclusions and Recommendations

Much of the Fox Island shoreline has undergone shore erosion and bluff retreat. In those areas where sufficient data exists, the bluff retreat rate is estimated to average 0.06 to 0.15 m/yr (0.2 to 0.5 ft/yr) in the period 1942 to 1970 (pre-FIL). In the post-1970 era, much of the bluff retreat at locations northwest from the FIL has been halted because numerous bulkheads and revetments have been installed there. Therefore, estimates for a shore retreat rate could not be made for that period.

FIL facilities do not cause significant blockage of sediment transport from the south sub-cell to the north sub-cell. Although the spatial coverage of data is limited, data analysis indicated that the FIL facilities may capture from 7 to 15 percent of the net sediment transport.

Results of numerical modeling of wave propagation to and past the FIL indicate that the facilities block sediment traveling from the north sub-cell to the south sub-cell.

Beach sediment at some locations north from the FIL is susceptible to erosion due to the interaction of bulkheads and waves.

Three geomorphic features are distinctive of the Fox Island shoreline:

- The cross-sectional configuration of the bottom slope is characterized by a narrow and relatively flat shelf extending from the upper beach to –1.5 m (–5 ft) MLLW that transitions abruptly to a steep underwater slope;
- The shoreline is rhythmic in plan form;
- The shore is backed by an high upland bluff.

These features have been modified by a combination of physical processes including waves, currents, tide fluctuations, and associated sediment transport and supply that cause natural long-term shore retreat. In a natural, undisturbed state (no FIL barges and pier, bulkheads, revetments, nor other coastal structures), the evolution and development of these features and processes was interdependent and the shore tended toward a state of dynamic equilibrium with prevailing processes.

Construction of the FIL has modified the natural development of the shore alignment and position in the proximity of the FIL. Shoreline modeling indicates that about 300 m (950 ft) of shore length to the north of the FIL is affected by the presence of the in-water facilities.

Bulkheads and coastal revetments have resulted in a reduction of sediment supply to the coastal system by restricting bluff erosion. Results of modeling indicate that at some limited locations northwest from the FIL, bulkheads in combination with the FIL might yield more shore retreat than would be the case with the FIL and no bulkheads.

Without the FIL facilities, bulkheads, and revetments, the shore erosion rate would reflect the historical rate of erosion of shores on Fox Island in the range of 0.06 to 0.15 m/yr (0.2 to 0.5 ft/yr). Assuming no bulkheads were constructed, but assuming the FIL facilities are in place, the sediment bypassing of the FIL (after equilibrium dimensions of the salient are attained) may result in more accretion on the upper beach of adjacent shores and a reduced rate of erosion of the shore to the north.

If the bulkheads were removed (or did not exist to start with), the shore would evolve to a relatively stable configuration, which would include a much wider upper shelf. This configuration would return sediment in larger volumes than the current conditions, and would occur regardless of the existence of the FIL facility.

Conclusions regarding alternatives evaluated for the EIS of relative effects on sediment movement and shoreline change can be drawn from Figures 50 through 55 and Table 6-1. In summary, concluding the relative impacts of the alternatives is based on:

- The rare occurrence of significant sediment transport events at this semi-protected shore;
- Consideration of the accuracy of an uncalibrated transport model in predicting the absolute transport rate;
- The small differences in transport rates between the alternatives and the existing condition; and
- The small differences in rates among the alternatives.

The conclusion is made that the small differences that can be inferred in shoreline impacts by the alternatives relative to the existing condition are essentially masked by larger scale processes responsible for actual sediment transport past the FIL and the adjacent stretch of shore. Modeling results and interpretation do not indicate that changes in shoreline effects by the FIL facility through implementation of an alternative should be an overriding reason for selection of a particular alternative.

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APPENDIX A

FIGURES REFERENCED IN TEXT OF REPORT

APPENDIX B

BEACH GRAIN SEDIMENT SIZE ANALYSIS

APPENDIX C

AERIAL PHOTOS